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Near-Surface Soil-Water Monitoring for Water Resources Management on a Wide-Area Basis in the Great Plains

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NEAR-SURFACE SOIL-WATER MONITORING FOR WATER RESOURCES MANAGEMENT ON A WIDE-AREA BASIS IN THE GREAT PLAINS

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ABSTRACT—In the Great Plains, soil water is one of the most critical factors related to sustainable production on cropland and rangeland, while the need for better water management grows in the face of increasing water demand during dry years. Soil water is also an important factor related to flood modeling and quantification of the boundary conditions in atmospheric models such as global circulation models. The objectives of this study were to install a wide-area automated soil-monitoring network, determine effective calibration procedures, and develop new products to illustrate the status of soil water. Soil-monitoring sensors were established at 51 sites across Nebraska under rain-fed conditions and under a grass cover. Four sensors were installed at each site at depths of 10, 25, 50, and 100 cm. The sensors were calibrated for three soil types: sandy, loamy, and clay. Data are collected daily, assessed for quality, and archived. Six quality-assurance (QA) tests were developed based on the properties of soil water, the statistical characteristics of the measurements, the soil properties, and the precipitation measurements. The quality-assured data from the network are used in maps to determine the spatial status of soil-water availability as expressed by the percentage of maximum available water in the layer (or profile). Data is also presented on the interannual and mean annual patterns of soil water across a range of climates, from semiarid to subhumid, in the Great Plains. The results of this study demonstrate the feasibility of monitoring soil water. This capability will be valuable in drought mitigation, water management planning, ecosystem research, and other studies. The dataset will be of great value for researchers in the Great Plains to quantify weather forcing, climate change, and the water balance, especially in rangeland areas.

Key Words: calibration, Great Plains, QA, sensor/probe, soil water, soil-water availability, soil-water network, Theta, Vitel

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INTRODUCTION

Increasing demands on land by agriculture, recreation, and preservation require a better understanding of hydrology, climate, and plant/soil interaction as an integrated system. Evapotranspiration, although critical to the hydrological water balance (Sridhar 2007), depends in turn on available soil water, both of which are fundamental components of the system. Demands for accurate soil-water data are consequently growing for both research and operational applications.

Accurate and reliable soil-water measurements and estimates also have important implications for continuing research in studies of land-atmosphere interactions. The use of land for crops leads to the need to account for evapotranspiration of crops. Investigators found the magnitude of evapotranspiration was constrained by various factors, including soil water (Denmead and Shaw 1962; Suder et al. 1981). In areas where crops are irrigated, regional evapotranspiration may increase by as much as 36% and can lead to cooling of the near-surface temperatures by 1.2°C. This makes soil water a key factor in changing climate as affected by agriculture-related land use (Adegoke et al. 2007).

Hong and Pan (2000) reported a strong positive feedback between soil water and simulated seasonal precipitation in implementing the NCEP Regional Spectral Model (RSM). Model simulations show that soil-water storage eventually affects moisture distribution within the lower boundary layer atmosphere (Hong and Pan 2000). Soil water was reported to play a role in seasonal predictability of surface climate anomalies (Wang and Kumar 1998) and simulating precipitation anomalies (Dirmeyer 1999, 2000). The Atmospheric Model Intercomparison Project (AMIP) reported that none of the AMIP models captured interannual variations in soil water (Robock et al. 1998). A large body of work suggests that experiments with long-term soil-water measurements should be included in future research (Entin et al. 1999; Leese et al. 2001; Mahmood and Hubbard 2004).

Soil water is accepted as one of the most critical factors for agricultural communities owing to its importance in crop selection, planting strategies, fertilizer rates, and irrigation requirements (Lawford 1992). The search for a reliable, affordable, and automated means of soil-water measurement, although intense, was not successful during most of the past century, during which high-quality data was generally not available (Hollinger and Isard 1994). For example, the gravimetric method is destructive and not amenable to automation. Nuclear methods are generally costly, difficult to implement, and a potential health risk. Despite the extra manpower required for neutron probes, a notable effort resulted in the collection of soil-water observations twice monthly at 23 sites around Illinois (Kunkel 1990). Other early networks are described in Robock et al. (2000). Sensors of the resistance and capacitive type, while able to be automated, require constant ionic concentration to be precise and may suffer from calibration drift (Schmugge et al. 1980). Tensiometers require frequent maintenance, exhibit hysteresis, cannot represent the range of water potential found in sand, and thus are fragile systems. Of the more recent sensors, time-domain reflectometers are friendly to automation but quite costly. Impedance probes are less expensive and are friendly to automation (Evett and Parkin 2005).

In this paper we discuss advances in monitoring soil water for typical soils found in the Great Plains (clay, silt, and sand types). Impedance probes were implemented in a statewide network in Nebraska to monitor soil-water resources. An earlier effort (Bosch et al. 2004) resulted in a soil-water network for validating remotely sensed data, but it covered a fairly small area (8,000 km^2) compared to the size of Nebraska (more than 200,000 km^2). A recent and valuable contribution to the literature, relevant to the southern Great Plains, is the work of Bradley et al. (2008), which discusses the addition of soil-water sensors at 116 sites in Oklahoma. Bradley et al. (2008) underscore the importance of monitoring over regional scales. In this paper, we show a similar effort in which we improve the calibration process by considering the soil type at the monitoring sites.

In the early stage, the soil-water data network utilized the Vitel (Stevens) HydraProbe (mention of a specific product name is for information purposes only and does not imply endorsement by the authors or their institution). Vitel is a sensor based on the concept of measuring the dielectric constant of soil and, together with an appropriate calibration curve, relating it to the volumetric water content of the soil. The Vitel probes were installed at 14 stations. The variability and noise of hourly soil-water data from the Vitel probes were found to be higher than those of Theta probes. This additional noise in the Vitel data led to higher random error in the Vitel soil-water measurements. Thus, the Vitel probes were replaced by the Theta probe (Delta-T Devices ML2x) in 2005 (You and Hubbard 2008).

A set of quality assurance (QA) tools including six QA procedures was developed to automatically review the daily observation for potential instrument failures

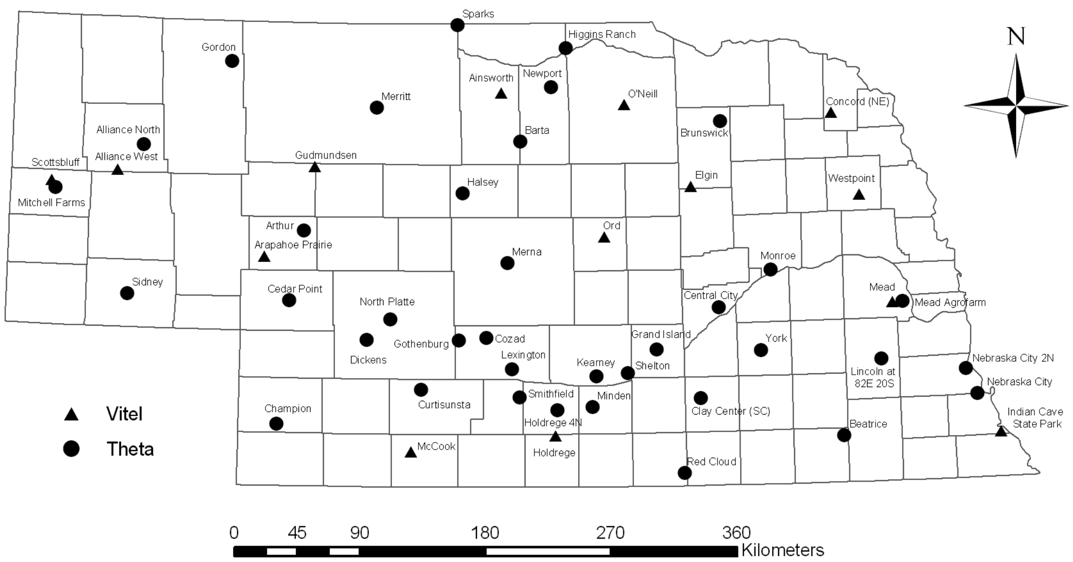

Figure 1. Nebraska soil-water network.

and unpredictable disturbances. The development and application of these QA tools were described in a separate paper (You and Hubbard 2008) and will be only briefly described below. In this paper we present the instrumentation, data archives, and calibration of soil-water probes in the monitoring network. Details of installation, calibration, and the mapping effort associated with the information are discussed. In addition, we present the currently available products in this network, such as the time series of measurements and the maximum water availability.

METHODS

Selection of Probes

Low-cost soil-water probes are preferred for large soil-water monitoring networks such as the Automated Weather Data Network (AWDN; Hubbard et al. 1983), which now have soil-water probes installed at 51 sites (see Fig. 1). In addition to being affordable, the sensors must be stable and relatively accurate probes to sustain the long-term continuous observations. The Theta probe (Delta-T Devices ML2x) was selected for this project. The Theta probe consists of a cable, a waterproof enclosure, and a sensing head (see Fig. 2A, or http://www.dynamax.com/ml2.gif). More information on the ML2 Theta probe can be found at http://www.dynamax.com/ML2.htm. The enclosure contains an oscillator and measurement circuitry, and the sensor head consists of three outer rods acting as a shield around one inner signal rod. All four rods act as an extra section of transmission line that has an impedance dependent on the dielectric constant of the medium. If this impedance is different from that of the internal transmission line, then a proportion of the 100 MHz signal is reflected back from the interface between the enclosure and the sensing head. The interaction between the transmitted wave and the reflected wave causes a standing wave to be formed where the difference in amplitude will give the relative impedance of the probe and thus the dielectric constant. Many authors (Topp et al. 1980; White et al. 1994; Whalley 1996) have confirmed the linear relationship between the square root of the dielectric constant $(\varepsilon)^{1/2}$ and the volumetric water content. More detailed information about the two types of probes utilized in this study can be found in Gaskin and Miller (1996), Seyfried and Murdock (2004), Blonquist et al. (2005), and Jones et al. (2005).

Installation of Probes

Theta probes were installed at each of 51 sites in the AWDN (see Fig. 1). A hole was excavated in the soil at each site and a sensor was installed at each depth: 10, 25, 50, and 100 cm (see Fig. 2B). All probes were installed horizontally by excavating a small opening and inserting the probes into the undisturbed wall of the hole at appropriate depths. During soil excavation, a soil sample was taken at each of the four depths; the sample was sealed and taken back to the laboratory for analysis. The water contents of these samples were later determined

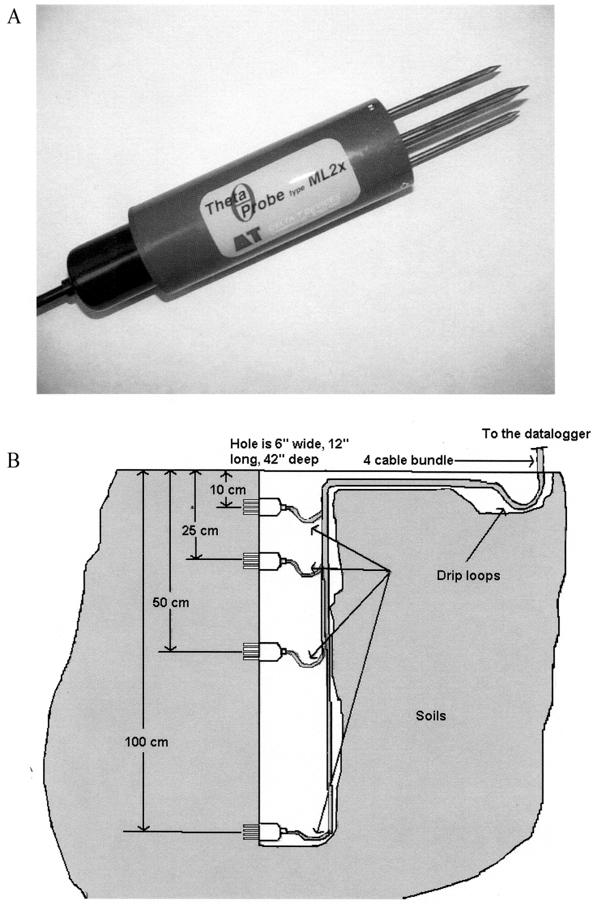

Figure 2. (A) Picture of Theta ML 2x probe. (B) Schematic of soil-probe installation at depths of 10, 25, 50, and 100 cm.

gravimetrically. Following installation of the sensors, the hole was backfilled with soil in reverse order to minimize the disturbances. Drip loops were formed in the cable to diminish the problem of water following the cable into the sphere of influence of the sensor. The first readings of the sensors were noted. These values were then entered into a database and the soil in each layer was classified as sandy, loam, or clay. Separate regressions were conducted on the stratified datasets to determine the linear or curvilinear relationship between soil-water content and probe readings in each soil type.

Calibration of Soil Water Probes

The field capacity and wilting point values were initially approximated with data from the Natural Resources Conservation Service. Both values were later refined from the actual measurements at times when field recharge and wilting point conditions were known to be present in the field for the sample of each layer. McMichael and Lascano (2003) show that it is necessary to calibrate probes based on data stratified by soil type instead of a single calibration for the whole soil profile. To obtain a better calibration of the Theta probe, we use the stratified calibrations rather than a single calibration. At this stage, the soil has not been broken down into fractions of sandy, silt, and clay, although a soil sample is normally a combination of the three. Other ongoing research focuses on the calibration and soil classification, the results of which will be adopted into the monitoring network in the future to refine the dataset since the raw data from Theta probes are also archived.

Quality Assurance of Soil-Water Data

The QA of soil-water data is addressed in a separate study (You and Hubbard 2008). Quality-assurance procedures and tests are implemented in the framework of a statewide network for soil-water monitoring. Extensive testing and analysis were conducted to determine the most effective QA algorithms for a soil-water dataset. Early results led us to conclude that standard QA tests for climate data would not be sufficient, so we undertook to design QA tests unique to soil water. This process resulted in six useable tests based on the properties of soil water, the statistical characteristics of the measurements, the soil properties, and the precipitation measurements. The first five tests are based on the properties of soil water, the statistical characteristics of the measurements, the soil properties, and precipitation measurements at the site. These tests were found to be effective in catching errors caused by instrument failures, and were an asset in the process of categorizing soil type. For instance, closer examination of soil type was carried out at Ainsworth when a considerable percentage of data was flagged as outliers. The sixth and most promising test is a more complex test based on the High Plains Regional Climate Center's soil-water balance model (Robinson and Hubbard 1990) and a spatial regression test. The test is able to identify outliers and generates reasonable estimates for missing data. The soil-water QA system continues to undergo tests to ensure stable and reliable operation. The QA methods lead to early identification of potential instrumental failures and other disturbances to the soil-water measurements.

Spatial Products

Spatial products displaying the percentage of maximum available water in the root zone were prepared using Grid Analysis and Display System (see Fig. 4).

The options include separate maps for each layer and a composite map representing the estimated soil water in the root zone. The root zone estimate is formed by using weighting coefficients (0.104, 0.208, 0.313, and 0.375) based on treating the measurement levels (10, 25, 50, and 100 cm) as the approximate midpoint of each of four layers. The mapping software performs a Cressman objective analysis (Cressman 1959) to translate the point measurements onto a grid suitable for map generation.

The soil-water data from the four depths were applied to estimate the maximum water availability in the soil layer up to a depth (d_t) of 122 cm (48 in). The four layers have depths d_1 (12.5, *0–12.5* cm), d_2 (25, *12.5–37.5* cm), d_3 (37.5, *37.5–75* cm), and d_4 (45, *75–122* cm), respectively. The spatial product, Percentage of Maximum Available Water (*PMAW*, %), provides a Nebraska-wide picture of the current soil-water conditions. Physically based spatial comparisons of soil-water observations were made possible by using physical soil properties to normalize soil-water observations. The computation of *PMAW* is:

$$PMAW = (\theta - \theta_{WP}) / (\theta_{FC} - \theta_{WP}) * 100 \qquad (1)$$

where θ is observed soil water, θ_{WP} is wilting point, and θ_{FC} is field capacity. θ_{FC} and θ_{WP} were determined for each layer by analyzing the historical observations. The computation can be applied to each of the four layers. The *PMAW* of the soil column to 1.22 m can be calculated using the normalized θ_{SW}, θ_{WP}, and θ_{FC} as in example of the normalized θ_{FC}:

$$\theta_{FC}(\text{column}) = (\theta_{FC}[10\text{cm}] \cdot d_1 + \theta_{FC}[25\text{cm})] \cdot d_2 + \theta_{FC}[50\text{cm}] \cdot d_3 + \theta_{FC}[100\text{cm}] \cdot d_4)/d_t \qquad (2)$$

Currently, a seven-day average soil water is used, and in the future the product will be expanded to other time periods. The product is available in contour and color-coded dot-map format.

RESULTS

The results of the calibration are shown in Figure 3. The calibration for sandy and silty soils resulted in coefficients of determination of 0.94 (Fig. 3A) and 0.95 (Fig. 3B), respectively. The calibration for clay soils was best fit with an exponential relationship and the coefficient of determination was 0.91 (Fig. 3B). The standard error of estimate on a volumetric basis was (0.03) for clay, slightly higher than the standard error of estimate for silt and sand (0.02). The uncertainty reported in the Bradley et al. (2008) paper was 0.05.

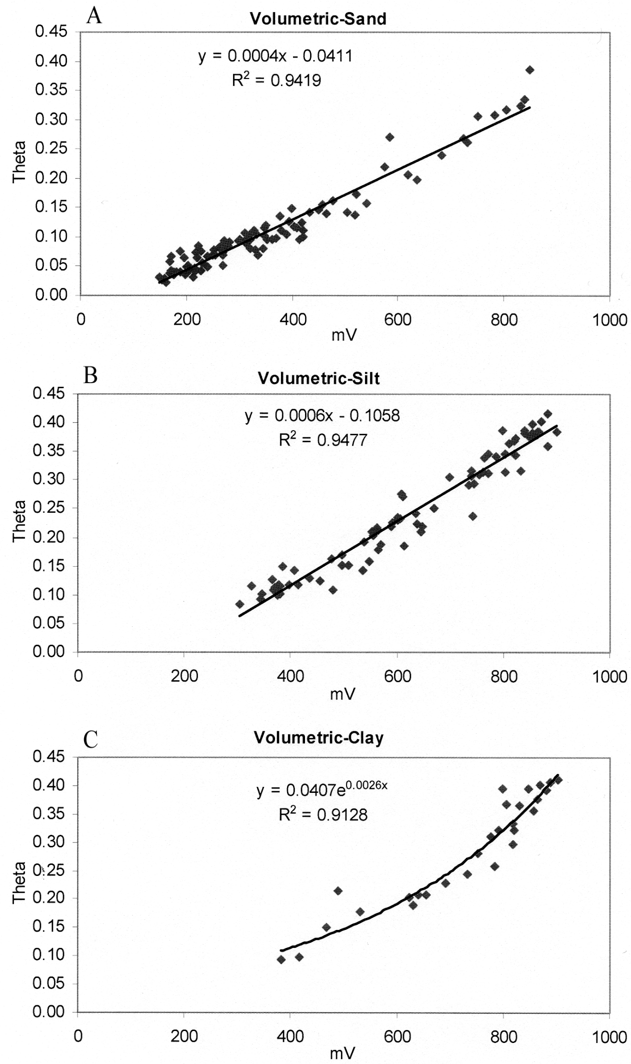

Figure 3. Calibration curves of Theta probes for different soil types: (A) sand, (B) silt, and (C) clay.

Spatial products based on the soil-water observation network are available interactively through the High Plains Regional Climate Center Web site, http://www.hprcc.unl.edu/soilm/ (accessed July 6, 2007). The spatial pattern of maximum available water is produced in either a shaded map or a dotted map for each of the four soil layers and for the root zone as a whole (calculated up to 1.22 m of soil layer depth). Figure 4 shows an example of the color-shaded map of the average maximum volumetric available water for a one-week period ending on August 29, 2006, for the state of Nebraska. (On the Web site, only color maps are presented, which are more readable.) The map is created from the measurement of the water content in the soil layers, which is directly related to the water stress of the plants or crops (Baier 1969; Suder et

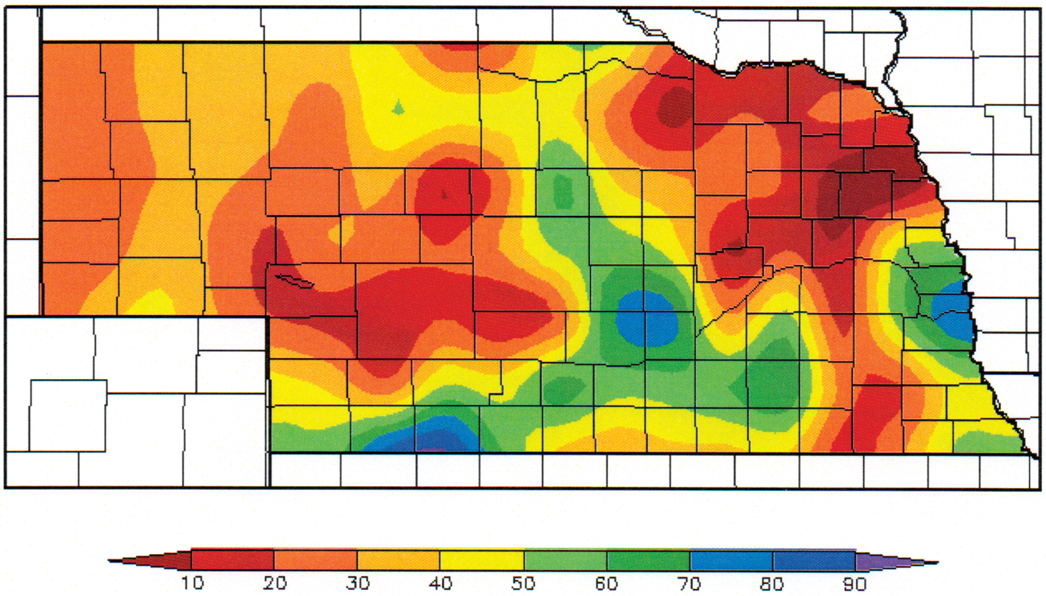

Figure 4. Example of the percentage of maximum available water in the root zone for August 30, 2006.

al. 1981). The water content is a more direct indicator of crop stress due to drought conditions than current drought indices calculated from precipitation. With the soil-water network, we are undertaking the development of a new drought index to predict the water status of crops.

The quality-controlled soil-water dataset was further analyzed for all of the AWDN sites to observe the seasonal trend and to evaluate the regional-scale soil-water pattern. The preliminary analysis included assessing the integrity of the dataset in all four layers of the soil column (10, 25, 50, and 100 cm) across Nebraska that encompasses eight climate divisions. Furthermore, soil-water profiles were plotted for some selected sites to characterize intersite variability and also to compute the root-zone soil water and volumetric water content that covers the period 1999-2005. Figure 5 shows the 1999-2005 average annual volumetric water-content curve at 50 cm for three selected sites: Mead (east), Ord (central), and Mitchell Farms (west).

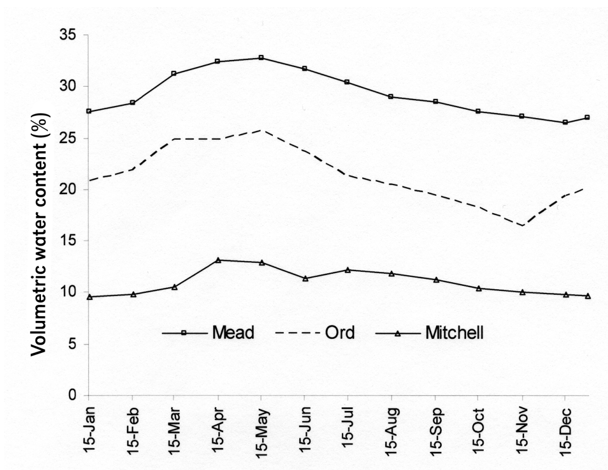

Figure 5. Average annual volumetric water-content curve at 50 cm for three selected sites over seven years.

During the period from 2000 to 2004, the Great Plains experienced severe droughts, with the most severe drought in 2002. The monthly soil-water content of the deep layers at 50 cm and 100 cm plotted in Figure 6 reveals the soil-water storage during the period. The soil-water content at Mead maintains a decreasing trend during the whole observation period. The 100 cm layer has a 7% declining trend in the past 10 years and the 50 cm layer has a 3% declining trend. The soil-water content exhibits relatively high variability at Ord compared to Mead because Ord is located in the Sandhills of north-central Nebraska where the soil has higher hydraulic conductivity. The water infiltration into the vadose zone at Ord is faster than at Mead, where clay soils dominate; however, the sandy-type soil cannot hold a large amount of water and thus the soil-water content drops quickly following a rainfall. In general, the soil-water content at the 100 cm layer and 50 cm layer has a declining trend at Ord during the drought years until 2004. The soil-water content at Mitchell Farm has some uncertainties related to

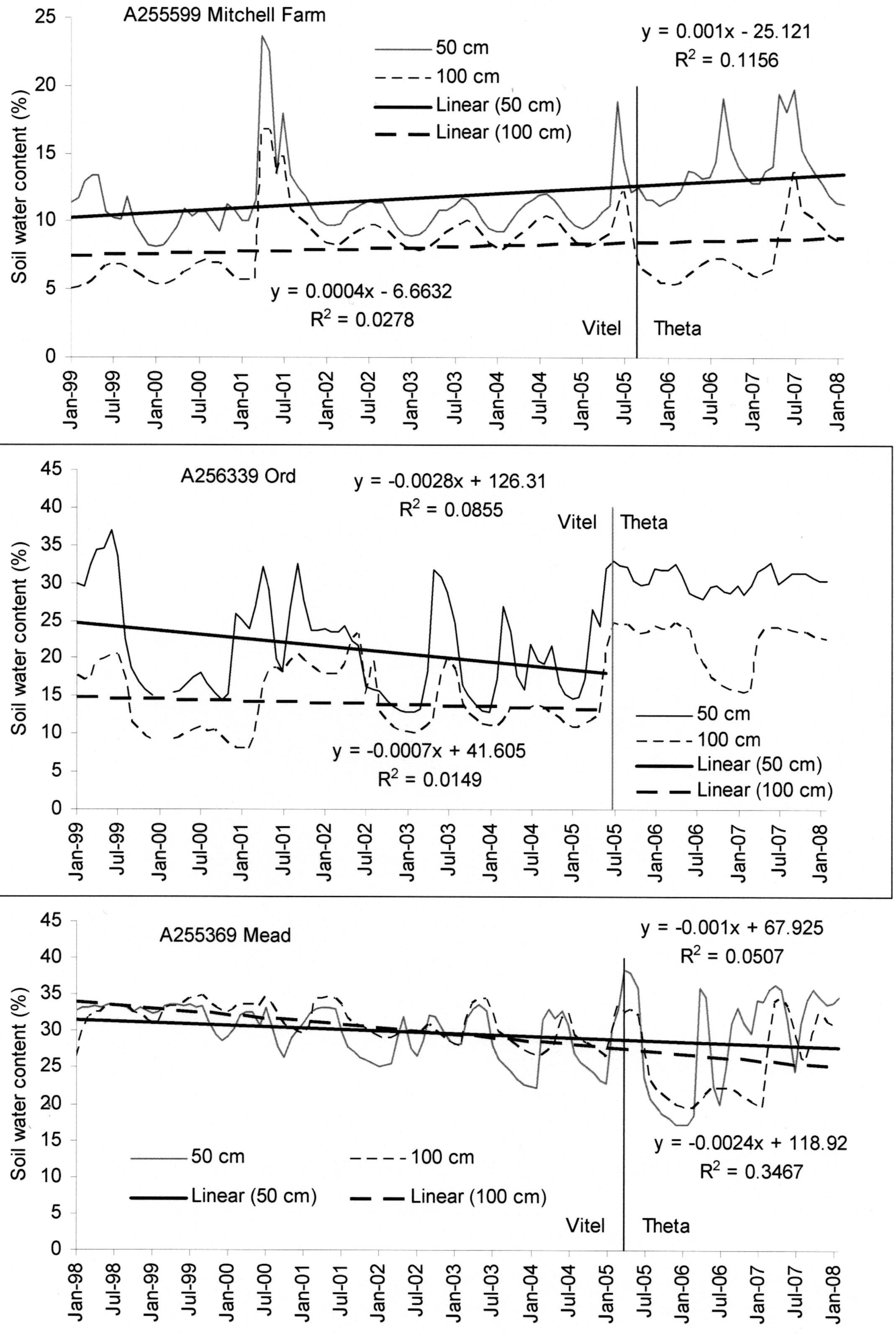

Figure 6. Soil-water content measurements of 50 cm and 100 cm layers and their trends at Mitchell Farm, Ord, and Mead.

the instrument replacement. The soil-water measurement at the 50 cm layer after 2005 has higher *FC* and *WP* values as measured by the Theta probes, compared to 2004 when Vitel probes were used. The measurement at the 100 cm depth indicated a lower *WP* value when a new Theta probe was installed. We are encouraged by the improvement found in typifying the soils before calibration and expect additional improvements in the future.

CONCLUSIONS

A statewide soil-water monitoring network was installed and operated successfully by collecting and archiving both the daily and the hourly soil-water data at 51 sites. In this case study, Theta probes are operated at depths of 10, 25, 50, and 100 cm below the surface at each of 51 sites. The daily soil-water data is available to the public on Web sites and hourly data is available per special request.

We found it necessary to calibrate probes based on data stratified by soil type, similar to the findings of McMichael and Lascano (2003). In this case we categorized each layer according to whether it was primarily sand, silt, or clay. The calibrations indicate a precision of 0.02 to 0.03 and coefficients of determination around 0.90 for all three soil types. We conclude that the sensors are characterized by a level of precision that is acceptable for automated soil-water monitoring. The use of quality assurance procedures in a network provides early awareness of potential problems caused by instrument failures and other disturbances. Thus the monitoring of soil water in the Great Plains is feasible on an operational basis.

The significant variability in soil water across space and time shown in our study provides us with insights into managing states' water resources and empowers both policy makers and stakeholders with alternate crop and land-use management practices, especially in drought years. While space-borne soil-water monitoring missions are being pursued for large-scale soil-water mapping, in situ measurements are vital especially for deeper layers. An automated network such as this can also supplement the calibration and validation efforts of such missions. We perceive that soil-water datasets from state and regional networks will aid in the task of modeling land-atmosphere feedbacks and water-cycle research where land-surface properties including soil-water conditions and in turn vegetation status are key factors at all scales from local to global.

The soil-water data is available to the public through the High Plains Regional Climate Center (http://hrcc.unl.edu/soilm). The percentage of maximum available water in the column is calculated for each site and then interpolated spatially. The soil-water dataset affords the opportunity to create a new drought index for drought monitoring and mitigation. Because soil water is a direct measurement of water available to plants, we no longer are limited by an indirect representation obtained from precipitation. The combined applications of crop-related models (e.g., Kunkel 1990; Robinson and Hubbard 1990) and the observations from water-content sensors installed in the grasslands can obtain relatively precise estimates of water demand.

Soil-water content is one of the least understood variables in the hydrologic cycle, and it has previously brought great uncertainties to the water balance. The variability of the soils leads to the difficulties in measuring and modeling soil-water content, and hence the quantification of runoff and evapotranspiration. A recent study by Nigam and Ruiz-Barradas (2006) has identified that global circulation models have considerable biases in water-balance quantification in the northern Great Plains; in their study, evapotranspiration in the Great Plains was found to be overestimated. Evapotranspiration in the Sandhills was overestimated because the soil-water availability was overestimated for the particular land surface. The statewide soil-water-content dataset described in this paper will be valuable for understanding the hydrologic cycle and climatic circulation over the Great Plains and thus correcting the bias in current models.

REFERENCES

Adegoke, J.O., R.P. Pielke, Sr., and A.M. Carleton. 2007. Observational and modeling studies of the impacts of agriculture-related land use change on planetary boundary layer processes in the central U.S. *Agriculture and Forest Meteorology* 142:203-15.

Baier, W. 1969. Concepts of soil moisture availability and their effect on soil moisture estimates from a meteorological budget. *Agricultural Meteorology* 6:165-78.

Blonquist, J.M., Jr., S.B. Jones, and D.A. Robinson. 2005. Standardizing characterization of electromagnetic water content sensors, pt 2: Evaluation of seven sensing systems. *Vadose Zone Journal* 4:1059-69.

Bosch, D., T. Jackson, V. Lakshmi, J. Jacobs, and S. Moran. 2004. In situ soil moisture network for validation of remotely sensed data. *Geoscience and Remote Sensing Symposium, IEEE International* 5:3188-90.

Bradley, G.I., J.B. Basara, D.K. Fisher, R. Elliot, C.A. Fiebrich, K.C. Crawford, K. Humes, and E. Hunt. 2008. Mesoscale monitoring of soil moisture across a statewide network. *Journal of Atmospheric and Oceanic Technology* 25:167-82.

Cressman, G.P. 1959. An operational objective analysis system. *Monthly Weather Review* 87:367-74.

Denmead, O.T., and R.H. Shaw. 1962. Availability of soil water to plants as affected by soil moisture content and meteorological conditions. *Agronomy Journal* 54:385-90.

Dirmeyer, P.A. 1999. Assessing GCM sensitivity to soil wetness using GSWP data. *Journal of the Meteorological Society of Japan* 77:367-85.

Dirmeyer, P.A. 2000. Using a global soil wetness dataset to improve seasonal climate simulation. *Journal of Climate* 13:2900-2922.

Entin, J.K., A. Robock, K.Y. Vinnikov, V. Zabelin, S. Liu, A. Namkhai, and T. Adyasuren. 1999. Evaluation of Global Soil Wetness Project soil moisture simulations. *Journal of the Meteorological Society of Japan* 77:183-98.

Evett, S.R., and G.W. Parkin. 2005. Advances in soil water content sensing: The continuing maturation of technology and theory. *Vadose Zone Journal* 4:986-91.

Gaskin, G.J., and J.D. Miller. 1996. Measurement of soil water content using a simplified 30 impedance measuring technique. *Journal of Agricultural Engineering Research* 63:153-59.

Hollinger, S.E., and S.A. Isard. 1994. A soil moisture climatology for Illinois. *Journal of Climate* 7:822-33.

Hong, S.-Y., and H.-L. Pan. 2000. Impact of soil moisture anomalies on seasonal, summertime circulation over North America in a regional climate model. *Journal of Geophysical Research* 105:29625-634.

Hubbard K.G., N.J. Rosenberg, and D.C. Nielsen. 1983. Automated Weather Data Network for agriculture. *Journal of Water Resources Planning and Management* 109:213-22.

Jones, S.B., J.M. Blonquist, D.A. Robinson, V. Philip Rasmussen, and D. Or. 2005. Standardizing characterization of electromagnetic water content sensors, pt. 1: Methodology (in soil water sensing). *Vadose Zone Journal* 4:1048-58.

Kunkel, K.E. 1990. Operational soil moisture estimation for the Midwestern United States. *Journal of Applied Meteorology* 29:1158-66.

Lawford, R.G. 1992. An overview of soil moisture and its role in the climate system. In *Soil Moisture Modelling and Monitoring for Regional Planning*, ed. J. Eley et al., 1–12. Proceedings of the NHRI Symposium, no. 9. National Hydrological Research Centre, Saskatoon, SK.

Leese, J.A., T. Jackson, A. Pitman, and P. Dirmeyer. 2001. GEWEX/BAHC International Workshop on Soil Moisture Monitoring, Analysis, and Prediction for Hydrometeorological and Hydroclimatological Applications. *Bulletin of the American Meteorological Society* 82:1423-30.

Mahmood, R., and K.G. Hubbard. 2004. An analysis of simulated long-term soil moisture data for three land uses under contrasting hydroclimatic conditions in the northern Great Plains. *Journal of Hydrometeorology* 5:160-79.

McMichael, B., and R.J. Lascano. 2003. Laboratory evaluation of a commercial dielectric soil water sensor. *Vadose Zone Journal* 2:650-54.

Nigam, S., and A. Ruiz-Barradas. 2006. Seasonal hydroclimate variability over North America in global and regional reanalyses and AMIP simulations: Varied representation. *Journal of Climate* 19:815-37.

Robinson, J.M., and K.G. Hubbard. 1990. Soil water assessment model for several crops in the High Plains. *Agronomy Journal* 82:1141-48.

Robock, A., C.A. Schlosser, K.Y. Vinnikov, N.A. Speranskaya, and J.K. Entin. 1998. Evaluation of AMIP soil moisture simulations. *Global and Planetary Change* 19:181-208.

Robock, A., K.Y. Vinnikov, G. Srinivasan, J.K. Entin, S.E. Hollinger, N.A. Speranskaya, S. Liu, and A. Namkhai. 2000. The global soil moisture data bank. *Bulletin of the American Meteorological Society* 81:1281-99.

Schmugge, T.J., T.J. Jackson, and H.L. McKim. 1980. Survey of methods for soil moisture determination. *Water Resources Research* 16:961-79.

Seyfried, M.S., and M.D. Murdock. 2004. Measurement of soil water content with a 50-MHz soil dielectric sensor. *Soil Science Society of America Journal* 68:394-403.

Sridhar, V. 2007. Evapotranspiration estimation and scaling effects over the Nebraska Sandhills. *Great Plains Research* 17:35-45.

Suder, R.A., K.E. Saxton, and R.G. Spomer. 1981. A predictive model of water stress in corn and soybeans. *Transactions of the ASAE* 24:97-102.

Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic determination of soil water content. *Water Resources Research* 16:574-83.

Wang, W., and A. Kumar. 1998. A GCM assessment of atmospheric seasonal predictability associated with soil moisture anomalies over North America. *Journal of Geophysical Research* 103:28637–646.

Whalley, W.R. 1996. Considerations on the use of time-domain reflectometry for measuring soil water content. *Journal of Soil Science* 44:1-9.

White, I., J.G. Knight, S.J. Zegelin, and G.C. Topp. 1994. Comments on “Considerations on the use of time-domain reflectometry for measuring soil water content.” *Journal of Soil Science* 43:1-13.

You, J., and K.G. Hubbard. 2008. Quality assurance of soil water data in ACIS: A case study in Nebraska. High Plains Regional Climate Center Report, http://hprcc.unl.edu/reports/. (Accessed March 2, 2009).